Characterization of Diagenetic Processes of the Late Maastrichtian – Danian Limestones in Ohafia, Ozu Abam and Arochukwu Areas of Southeastern Nigeria

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Abstract
Vast deposits of limestones of Late Maastrichtian to Paleocene age occur in the Ohafia, Ozu-Abam and Arochukwu areas of southeastern Nigeria. The present study sought to gain insight into the evolutionary history and conditions of formation of the limestones, through detail investigations and characterization of the diagenetic processes that affected the rock. The diagenetic processes considered include cementation, neomorphism, micritization, compaction and dissolution. Dolomitization process was not considered because it was conspicuously absent in all the thin sections examined. The cement types observed include blocky or equant mosaic calcite cement, drusy mosaic calcite cement, micritic calcite cement with a meniscus fabric, and acicular aragonite cement. Micritization of bioclasts in the limestones is very low and is characterized by thin micritic envelopes covering the grain surfaces. Neomorphism is a prominent feature of the limestones and is responsible for the formation of large sized crystals in the limestones. Compaction is discernible by a parallel alignment of fractures in a thin section. Dissolution in the limestones is shown by the presence of solution cavities in the thin section. Dolomitization were not observed in the limestones. The various diagenetic transformations that the Late Maastrichtian to Paleocene limestones of Ohafia, Ozu-Abam and Arochukwu areas of southeastern Nigeria have undergone corroborates development under shallow marine conditions. In particular, the presence of drusy mosaic as a cement type is an indication of the relevance of meteoric phreatic conditions in the evolutionary history of the rock.
Keywords: Diagenesis, Carbonate, Petrography, Nigeria

1. Introduction
Several studies have been carried out on the Late Maastrichtian to Danian limestones of the Nsukka and Imo Formations in Ohafia - Ozu Abam and Arochukwu areas in southeastern Nigeria (Ekwere *et al*., 1994; Ephraim and Odumodu, 2015; Kumaran and Rajshekhar, 1992; Mbuk *et al.,* 1994; Ibe and Ogezi, 1997, 1999; Oti, 1983; Reyment, 1965). Reyment (1965) observed that the Nsukka Formation outcropping southwards of Okigwe consist of bands of fossiliferous limestones interbedded with sandstones, shale's and sandy shale. Oti (1983) discussed the mineralogy, petrology and incipient phosphate mineralization of the limestones in Arochukwu and Ohafia areas. Kumaran and Rajshekhar (1992) investigated the foraminiferal linings in the Late Cretaceous to Paleocene sediments in the Ohafia and Ozu Abam areas. Mbuk et al (1994) discussed the significance of some fossils found in the upper parts of the formation. Ekwere et al (1994) investigated the resistivity, chemical characteristics and raw materials potentials of Tertiary limestones in Obotme in the southern part of the study area. Ibe and Ogezi (1997, 1999) discussed the chemical and industrial characteristics of Ohafia – Ozu Abam limestones. Ephraim and Odumodu (2015) studied the petrology, geochemistry and industrial utilization of the limestones. The present study isfocused on the diagenetic processes experienced by the Late Maastrichtian to Paleocene limestones, after sedimentation. In carbonate rocks, diagenetic processes consist of six main types, namely; cementation, micritization, neomorphism, dissolution, compaction and dolomitization (Saffar et al, 2010). These processes are investigated as it applies to the Late Maastrichtian to Danian limestones of Ohafia – Ozu Abam and Arochukwu areas in southeastern Nigeria.

2. Study Area
The study area lies in the southern parts of the Anambra basin, It is bounded by longitudes 5°22'N and 5°40' N and latitudes 7°42'E and 7°55'E (Fig. 1). Limestone outcrops in the study area include those of; Osusu Ndiawa, Ndi Ukpeze and Kalaiyi streams in Ndi Uduma Ukwu and Ndianku. Others include outcrops in Akoli River, Oboro Village, Ohafia Ozu Abam road, Isiugwu track road Ndi Oji, Ogbugbandu plantation, Ndi Oji, Ogbueke and Aboichara streams at Ndi Okorie, Ogo Ubi Ndi Orioma road, Ozu Abam, Orua stream, at Eziafor, Ihule stream at Okrika, Ndi Oji, Ndi Ikwesi Ikpeta at Ndi Okwara, Orauke at Ndi Okereke and Ihiagwa stream at

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Asaga village, Arochukwu. For the present study, limestone samples were studied mostly from outcrops of: Ihule stream at Okrika, Ndi Okoyi and Kalaiyi Oruebine streams at Ndi Uduma, along Ohafia – Ozu Abam road, Ogbugbandu plantation, Isiugwu – Ndi Oji track road at Ndioji, Orua stream at Eziafor and Ihiagwa stream at Asaga Village in Arochukwu (Fig. 1).

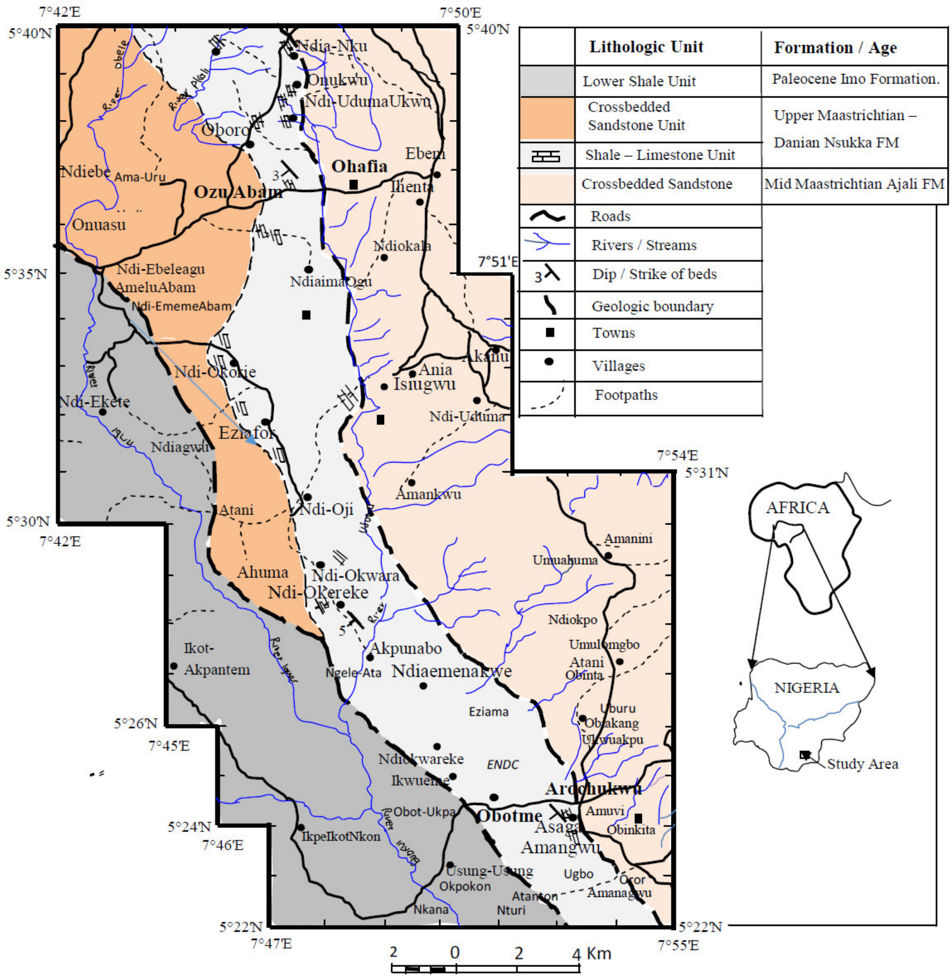

Fig. 1: Geological map of the study area (after Ephraim and Odumodu, 2015)

2.1 Geological and Stratigraphic Setting

The stratigraphic succession in southeastern Nigeria is shown in Table 1, while the geologic sketch map of Anambra Basin is presented in Fig. 2. The stratigraphic succession in the Anambra Basin has been discussed by several workers (Reyment, 1965; Murat, 1972; Petters, 1978; Agagu et al, 1985; Hoque and Nwajide, 1984). For brevity, during the Santonian tectonism, the Anambra and Afikpo platforms became downwarped to form the Anambra Basin and Afikpo syncline respectively (Murat, 1972; Petters, 1978).

Sedimentation commenced in the Anambra Basin after the post Santonian deformation and uplift of the Abakaliki – Benue Trough. The uplifted Abakaliki Anticlinorium thus supplied sedimentary detritus that were used to fill the basins from Late Cretaceous to Early Paleocene.

The part of the Nsukka Formation that is exposed within the study area consists of two major lithologic units, namely: the shale – limestone unit and the crossbedded sandstone unit. The shale – limestone unit is the lowest stratigraphic unit as it directly overlies the Ajali Formation. It is overlain by the crossbedded sandstone unit. The shale – limestone unit is composed of carbonaceous shales, fossiliferous to sandy limestones and clays. The carbonaceous shales are micaceous, bluish black, and thinly laminated shale (Odumodu, 2014), while the limestone member contain several fossils, including gastropod Nerinella and bivalve Ostrea. The crossbedded sandstone unit consists of planer crossbedded sandstones and bioturbated fine to coarse grained pebbly sandstone with Ophiomorpha and Chondrites ispp. This crossbedded sandstone unitis overlain by the Lower Shale unit of the Imo Formation.

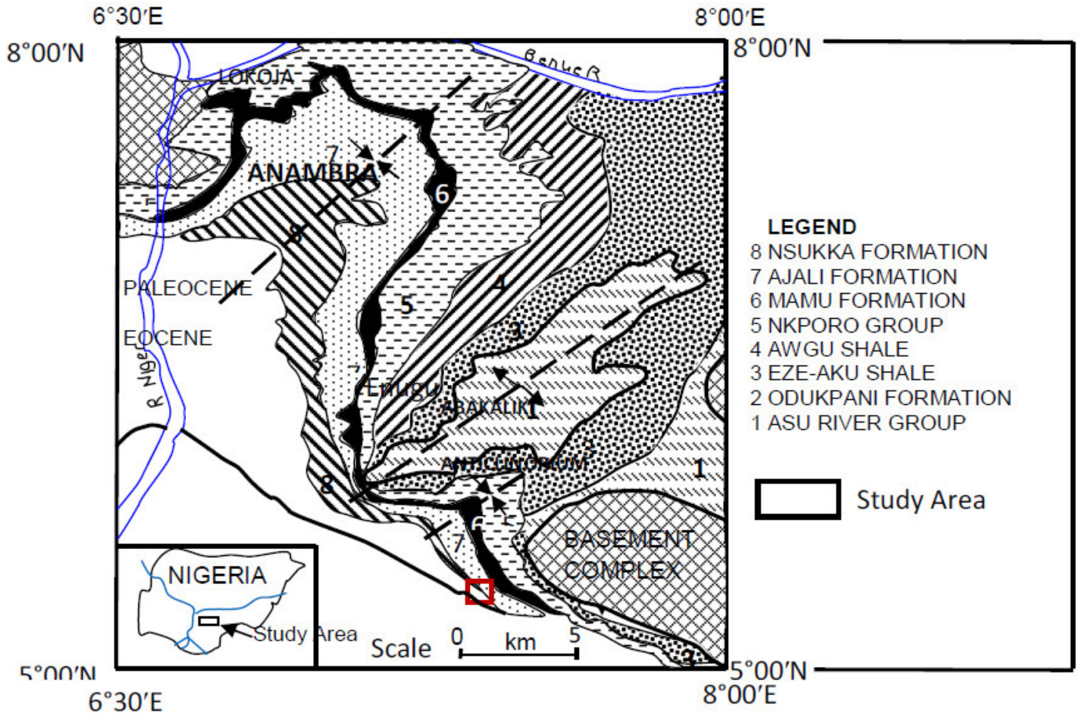

Fig. 2: Geologic map of southeastern Nigeria showing the location of the study area

2.2 Petrography and Mineralogy

Detailed petrography and mineralogy of the Upper Maastrichtian – Danian limestones of Ohafia – Ozu Abam – Arochukwu area has been reported elsewhere (see Ephraim and Odumodu, 2015). Nevertheless, for comprehension purposes, the petrographic framework of the limestones is given in Table 1. As shown (Table 1), the limestones are dominated by grain supported bioclastic packstones, grainstones and a few bioclastic mud supported wackestones.

TABLE 1. Petrographic framework of the Upper Maastrichtian – Danian limestone of Ohafia – Ozu Abam – Arochukwu areas

Sample Location		Composition of Limestone (in wt%)				Composition of Allochems (in wt%)				Folk (1974) Classification Scheme	Dunham (1962) Classification Scheme
Label	Description	Allochem	Micrite	Sparite Cement	Ferrugeneous fragments	Intraclast	Oolites	Fossils	Pellets		
S1	Ogoubi Ndiorioma Rd.	45	15	35	5	2	0	23	75	Pelsparite	Packstone
S2	Oduenyi Limestone	65	5	20	10	80	2	15	3	Intrasparite	Packstone
S3	Ndianku	45	15	35	5	2	0	23	75	Pelsparite	Packstone
S4	Ndi Uduma Ukwu	65	10	20	5	10	0	65	35	Biosparite	Packstone
S5	Ndi Ukpoyi	65	10	20	5	5	0	85	10	Biosparite	Packstone
S4	Akoli River	40	10	50	5	0	0	65	35	Biosparite	Packstone
S7	Ndi – Okereke	25	20	45	10	10	0	55	35	Biopelsparitre	Packstone
S8	Oboro	66	0	25	9	4	0	79	17	Biosparite	Grainstone
S9	Ohafia –Ozu Abam Rd.	80	5	10	5	10	0	60	30	Biosparite	Packstone
S10	Ndi Okoyi-Ndi Uduma	70	5	25	0	0	0	95	5	Biosparite	Grainstone

The allochemical constituents are higher and are closely followed by sparry calcite, while carbonate mud matrix or micrite is lower, and ferruginous fragments are relatively insignificant. The bioclasts, which includes bivalves, mollusks especially gastropods, foraminifera (mainly Miliolina) and ostracods, make up about 90% of the allochems (Table 1). Most of the bivalves and mollusks have laminated structures which is suggestive of an aragonitic origin (Fig. 3a and 3b). Most of the bioclasts have been recrystallized to calcite while some are micritized; the mollusks shells shown in Fig. 3c are filled with recrystallized calcite (spar).

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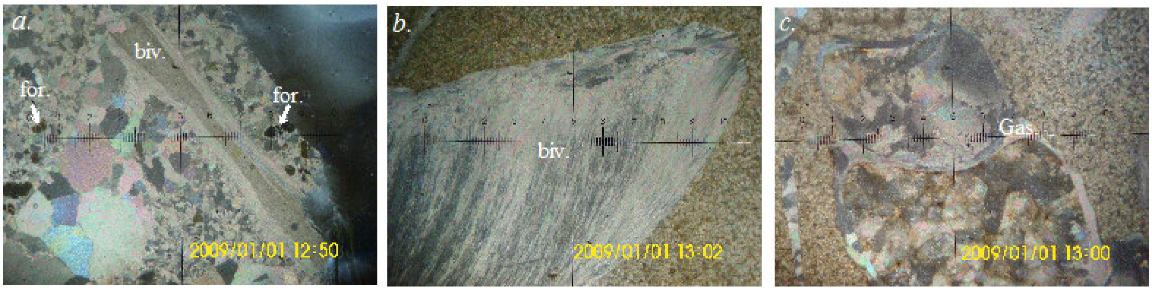

Fig. 3: Photomicrographs of limestones showing both laminated structures and recrystallization features. The laminated structures are well preserved on the bivalve (biv) fragments shown in (a and b). Although the foraminifera (for) shown in (a) exhibits recrystallization feature, this attribute is well displayed in (c), where a punctuated clear gastropod (Gas) fragment that appears at the center of the slide experiences partial and preferential replacement by microcrystalline calcite, with consequent destruction of the primary shell structure.

In terms of mineralogy, calcite constitutes the most abundant mineral, while quartz and iron minerals are subordinate. In most of the thin sections, quartz grains are distributed interlocked with calcite. The calcite grains, which occur mostly in aggregate, comprises predominantly of medium- to coarse-grained, rounded to subrounded equigranular grains with few larger discrete spar occurring within matrix of very fine grained materials. The quartz show polycrystalline nature and sutured contacts under plane polarized light, which is indicative of partial recrystallization. Little or no flaky minerals or sulfide-bearing minerals occur.

3. Materials and Methods

The methodology utilized in the present study includes both field studies and detailed petrological examination of mostly unstained thin sections. A total of eight representative samples of limestones were cut into thin sections. The prepared slides were viewed under PPL and CPL using the petrological microscope to obtain information on the lithology, fabric, texture and mineralogy. The colour atlas for carbonate rocks of Adams and Mackenzie (2001) aided in the identification of the grain types and textures .

4. Results and Discussion

4.1 Diagenetic Features

Detailed petrographic studies were conducted to decipher the diagenetic settings of the Late Maastrichtian to Danian limestones of Ohafia – Ozu Abam and Arochukwu areas from thin sections. The diagenetic features identified and interpreted are discussed under cementation, micritization, neomorphism, dissolution and compaction. Dolmitization is conspicuously missing because the studied limestones have not undergone dolomitization process.

4.1.1 Cementation

According to Saffer et al (2010), cementation is an important diagenetic process that help in forming hard limestones from weak sediments as cement often endows strength and stability to calcareous sediment (Nizami et al, 2006), Cement often occurs in places where a great amount of intra particle fluids are oversaturated. The composition of the cementing material of the Late Maastrichtian to Danian limestones of Ohafia – Ozu Abam and Arochukwu is mostly carbonate (calcite and aragonite) while iron oxide or ferroan types occur sparingly. The identified types of cements are mostly the cavity and pore filling type, while syntaxial rim types are rare. In terms of morphology, the blocky or equant mosaic calcite cement (Fig.4a) were mostly observed, followed by the drusy mosaic calcite cement (Fig.4b), acicular aragonite cement (Fig. 4c) and micritic calcite cement (Fig. 4c & 4d). The blocky or equant mosaic calcite cement is characterized by cements possessing calcite crystals of equal sizes (Fig. 4a). In the drusy mosaic calcite cement, the crystals increase in size away from the substrates towards the centre of the original pore spaces (Fig. 4b). Qureshi et al (2008) observed that the drusy mosaic in the Jurassic Samana Suk Limestone of Pakistan are characteristic of meteoric phreatic environments, which may also continue into burial environments. The acicular aragonite cements consists of broadly isopachous cement which is usually distinguished by the ragged outline of the cement (Fig. 4c). The micritic calcite is constituted by cements of micritic composition (Fig. 4c & d). Aragonite occurs exclusively as acicular aggregates; whereas calcite occurs in a variety of forms, including microcrystalline, peloidal, and bladed spar. All these are common shallow-marine cements (Macintyre 1977; Macintyre and Marshall 1988; Sherman et al., 1999). It appears as if the early cements precipitated as fibrous/acicular cement, obtained mostly from the decomposition of aragonite, while the intergranular cements comprising the blocky / equant cement and drusy mosaic types precipitated as later pore filling calcite diagenetic cements.

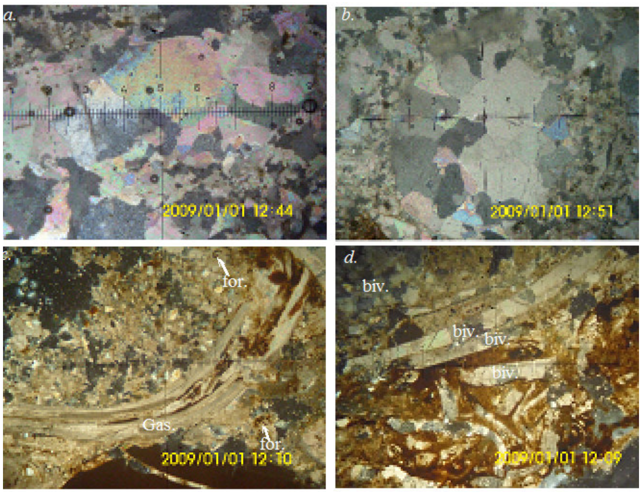

Fig. 4: Photomicrographs of bioclastic limestones showing the different cement types, notably: (a) blocky or equant mosaic (b) drusy mosaic (c) micritic and acicular calcite cement and (d) micritic calcite cement type. The bioclastic components shown include foraminifera (for), gastropod (Gas) and bivalves (biv.).

4.1.2 Micritization

Micritization is the process whereby the margins of carbonate grains are replaced by micrite at or just below the sediment / water interface. It can also be viewed (Saffer et al, 2010) as the processes whereby bioclasts or non skeletal grains are destroyed by non calcareous algae, fungi and bacteria and forming a micritic cover around them. According to Maryanto (2012), during micritization, carbonate mud are usually concentrated at the edge of carbonate grains, forming what some researcher refer to as micrite envelops. The process of micritization involves microbes attacking the outside of grains by boring small holes in them, which are later filled with micrite cement (Adams and MacKenzie, 2001). Micritization of bioclasts in the investigated limestones is very low, and denoted by the occurrence of outline of thin micritic envelope on some bioclasts . Only a few micritized bioclasts has been observed (Fig. 5a, 5b and 5c). In Figs. 5a and 5d parts of the bioclast surfaces are micritized.

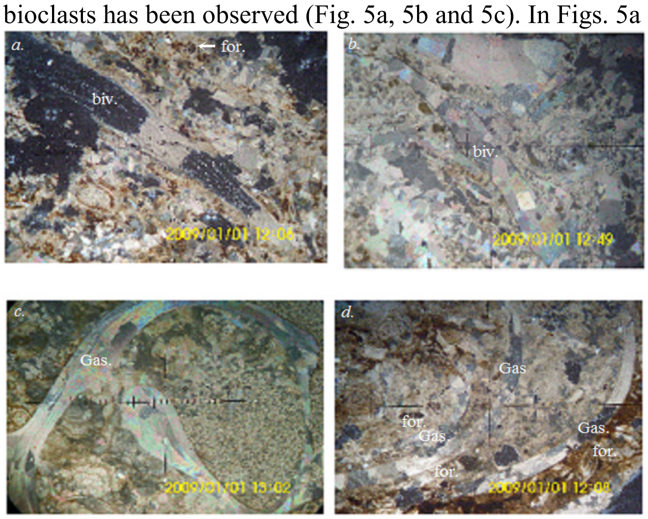

Fig. 5: Photomicrographs of bioclastic packstones showing micritization features on bioclasts. The bioclastic components include foraminifera (for), gastropod (Gas) and bivalves (biv.). Note the thin micritic envelop around the bioclasts, especially in (a and d)

4.1.3 Neomorphism

Neomorphism is defined as the process leading to the formation of large sized crystals (Saffer et al, 2010). Neomorphism is an important process in the overall diagenetic transformation of these limestones as observed in thin sections with large crystals of calcite. Neomorphic features are observed in limestones at Orua stream Eziafor, Isiugwu track road Ndioji, Ohafia road Ozu - Abam road and Kalaiyi –Oruibine stream at Ndi-Uduma (Fig. 6a, 6b, 6d and 6e).

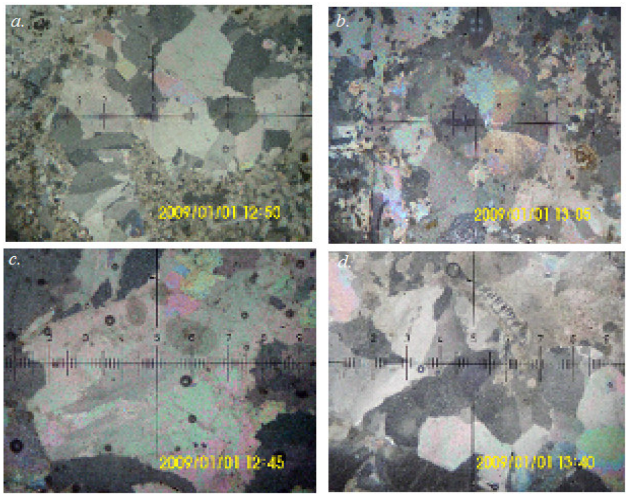

Fig. 6: Photomicrographs of bioclastic limestones showing various neomorphic features. In these sections, the original bioclastic textures and fabrics are partially destroyed

4.1.4 Compaction

Compaction is an important aspect of diagenesis because it is a direct function of overburden pressure. In the present study, mechanical compaction is suggested by the fracturing of coarse recrystallized calcite crystals observed in slides collected from Isiugwu – Ndioji track road (Fig. 7). In these slides, many of the crystals of calcite also undergo undulose extinction which is usually a direct response of crystals to pressure. In such crystals, the crystallographic axes are distorted by dislocation creep, creating various sets of crystallographic axes across the same crystal, causing the crystal to have a wavy extinction.

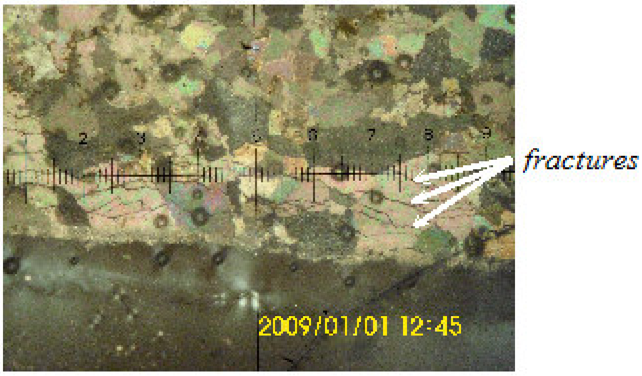

Fig. 7: Photomicrograph of bioclastic packstones showing parallelism of fractures in calcite as an evidence of compaction

4.1.5 Dissolution

The investigated carbonate rocks are subjected to dissolution due to the influence of tropical to subtropical climatic condition to which they have been exposed to. Some parts of the rock unit can be said to be very porous and permeable while other sections are not as porous and permeable. This factor is a direct function of the presence of solution cavities (dissolution). In the rock under study. Incidentally, the samples with the highest degree of dissolution / solution cavities also contain the largest numbers of forams (Miliolina) and the highest degree of micritization

5. Conclusion

The thin section studies have revealed that the limestones consists of grain supported bioclastic packstones, grainstones and a few mud supported wackestones. This study has equally shown that the limestones have undergone five different diagenetic effects including cementation, micritization, neomorphism, dissolution and compaction. The dolomitization processes have not been observed in the limestones. The major cement types include the blocky or equant mosaic calcite cement, the drusy mosaic calcite cement, the micritic calcite cement with a meniscus fabric and the acicular aragonite cement. Compaction is evidenced by the parallel alignment of fractures in a particular direction. Dissolution is shown by the presence of solution cavities in the thin sections of the limestones. This study has shown that the Late Maastrichtian to Paleocene limestones in the Ohafia – Ozu – Abam Arochukwu areas in southeastern Nigeria has undergone some diagenetic changes since after sedimentation. Such diagenetic transformations include cementation, micitization, neomorphism, dissolution and compaction.

Future studies would involve correlations and investigations of the diagenetic processes of the subsurface prospects after prior detailed geological study, supported with the opening of trenches in target areas have revealed more in terms of the subsurface structure of the unit

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